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EP 0887624 A3 | **EP 0806642 A1**
WO 1991/002959 A1 | **NL 008401361 A**
US 6385561 B1 | **US 6310702 A**
US 20020063866 A1

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INT CL[7] **G01D, G01H, G01K, G01L, G01M, G01N, H04B**
Other: **Online: WPI, PAJ, EPODOC**

(54) Abstract Title: **Optical fibre sensor**

(57) To detect disturbances (changes in physical configuration) in optic communication or transmission media such as fibre-optic cables 180, a source 110 provides pulsed laser light, a circulator 150 inputs the pulsed laser light into the fibre-optic cable and receives backscattered radiation from the cable 180. Detection stage 160 detects the amplitude of radiation backscattered from the cable 180 as a function of time, the backscattered radiation being caused by pulses of laser light input into the cable 180 at a first end. Successive returns may be analysed and may be correlated to indicate the existence and/or location of a disturbance.

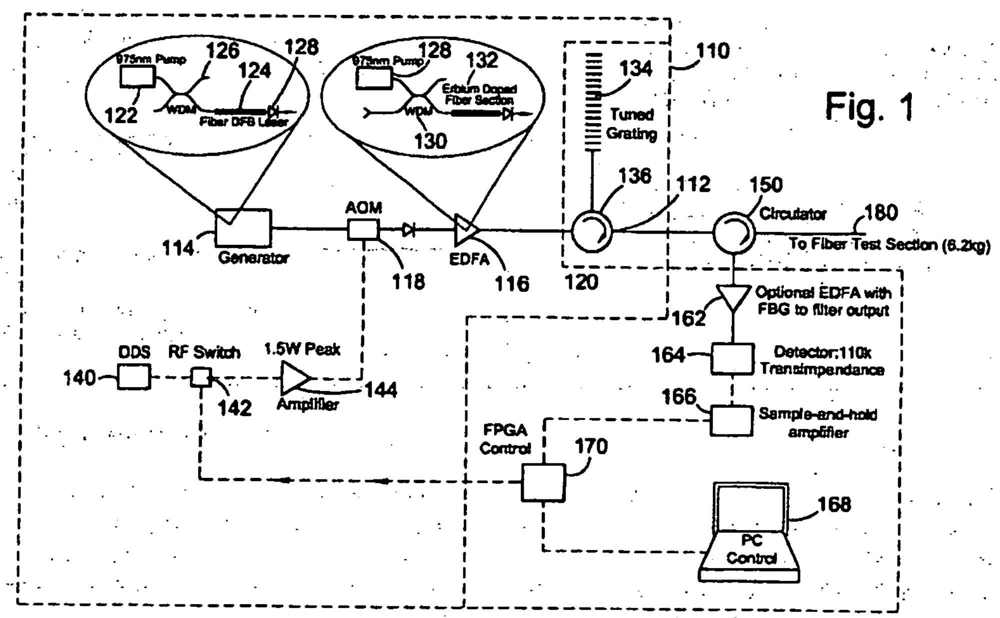

Fig. 1

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

The print reflects an assignment of the application under the provisions of Section 30 of the Patents Act 1977.

GB 2 401 738 A

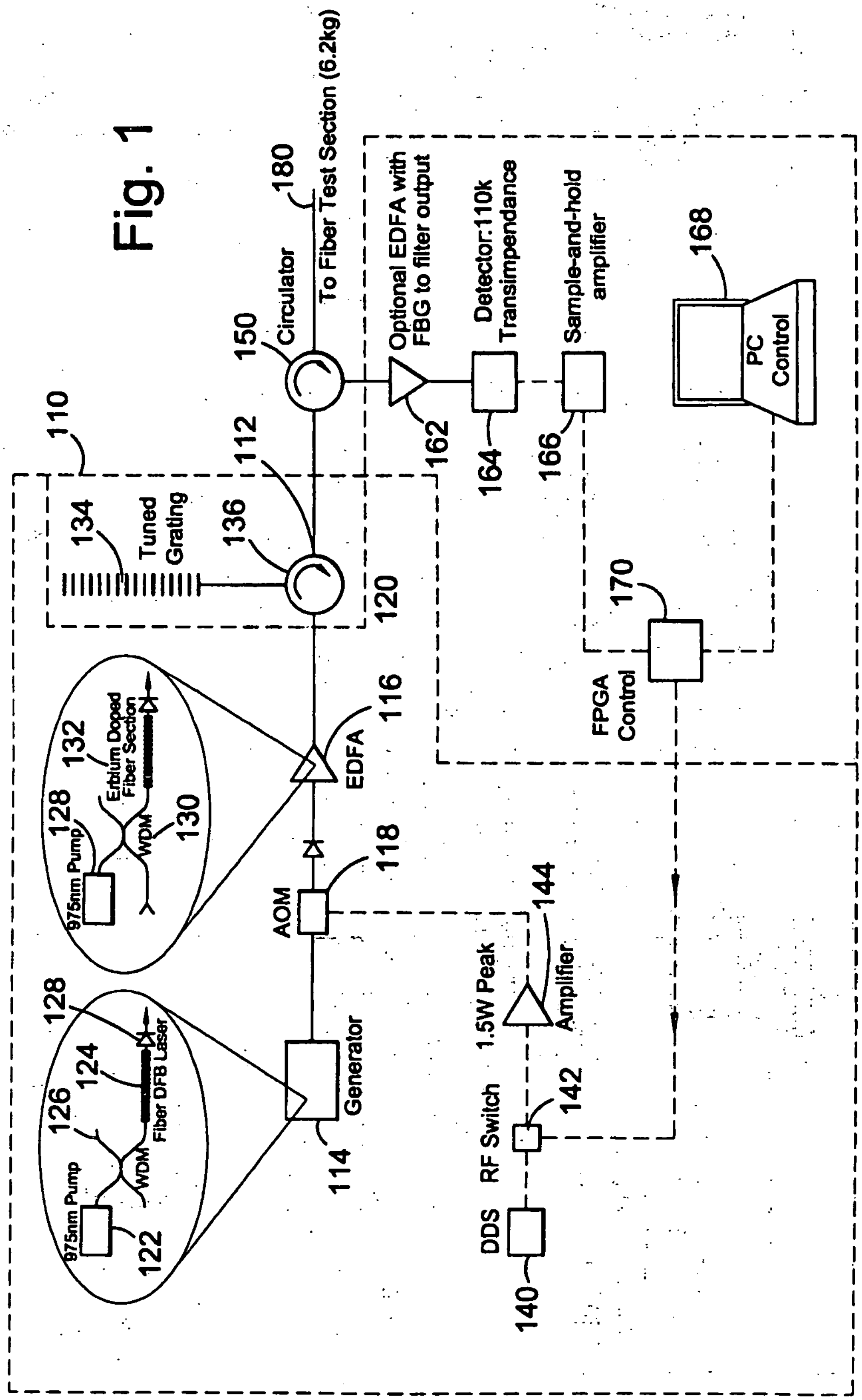
To Fiber Test Section (6.2kg)
180
Circulator
150
Optional EDFA with FBG to filter output
162
Detector:110k Transimpendance
164
Sample-and-hold amplifier
166
168
PC Control
110
112
134
Tuned Grating
136
120
170
FPGA Control
132
Erbium Doped Fiber Section
128
975nm Pump
WDM
130
EDFA
116
118
AOM
144
1.5W Peak Amplifier
142
RF Switch
DDS
140
128
124
126
975nm Pump
WDM
Fiber DFB Laser
122
Generator
114

Fig. 1

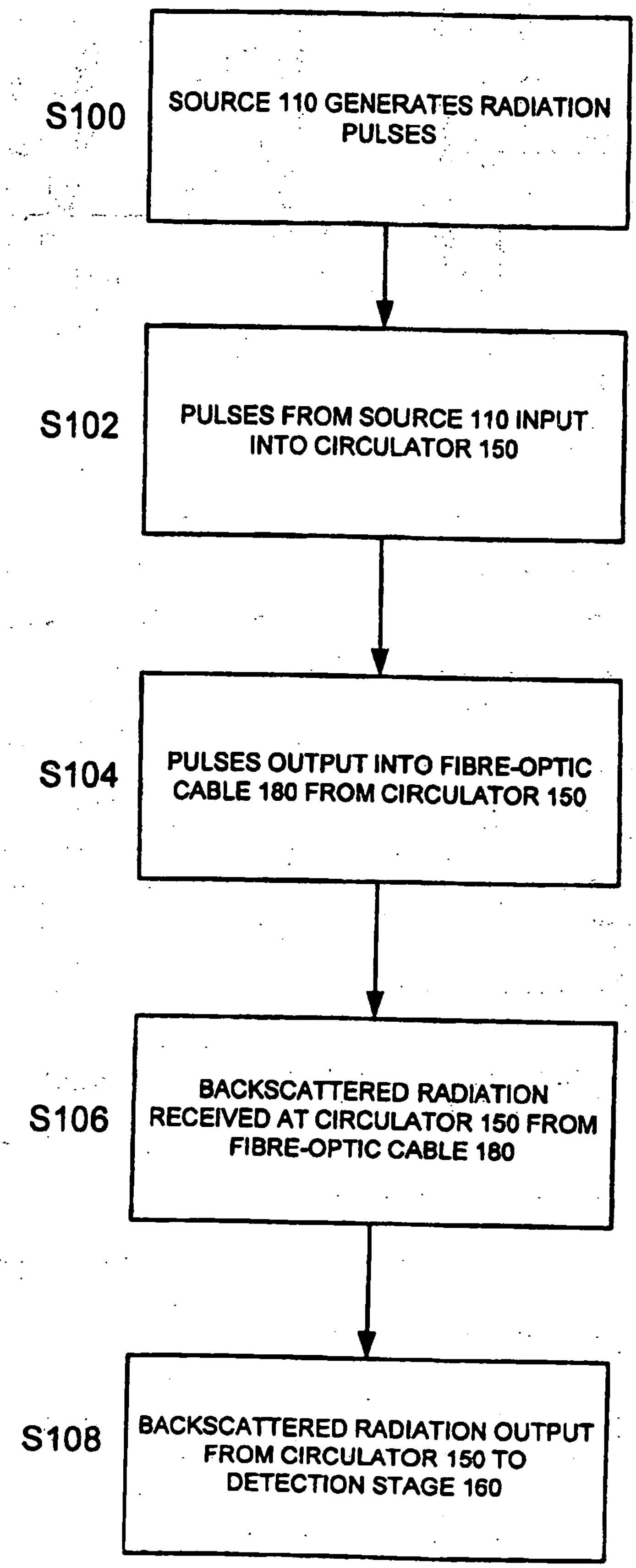
S100
SOURCE 110 GENERATES RADIATION PULSES
S102
PULSES FROM SOURCE 110 INPUT INTO CIRCULATOR 150
S104
PULSES OUTPUT INTO FIBRE-OPTIC CABLE 180 FROM CIRCULATOR 150
S106
BACKSCATTERED RADIATION RECEIVED AT CIRCULATOR 150 FROM FIBRE-OPTIC CABLE 180
S108
BACKSCATTERED RADIATION OUTPUT FROM CIRCULATOR 150 TO DETECTION STAGE 160

Fig.2

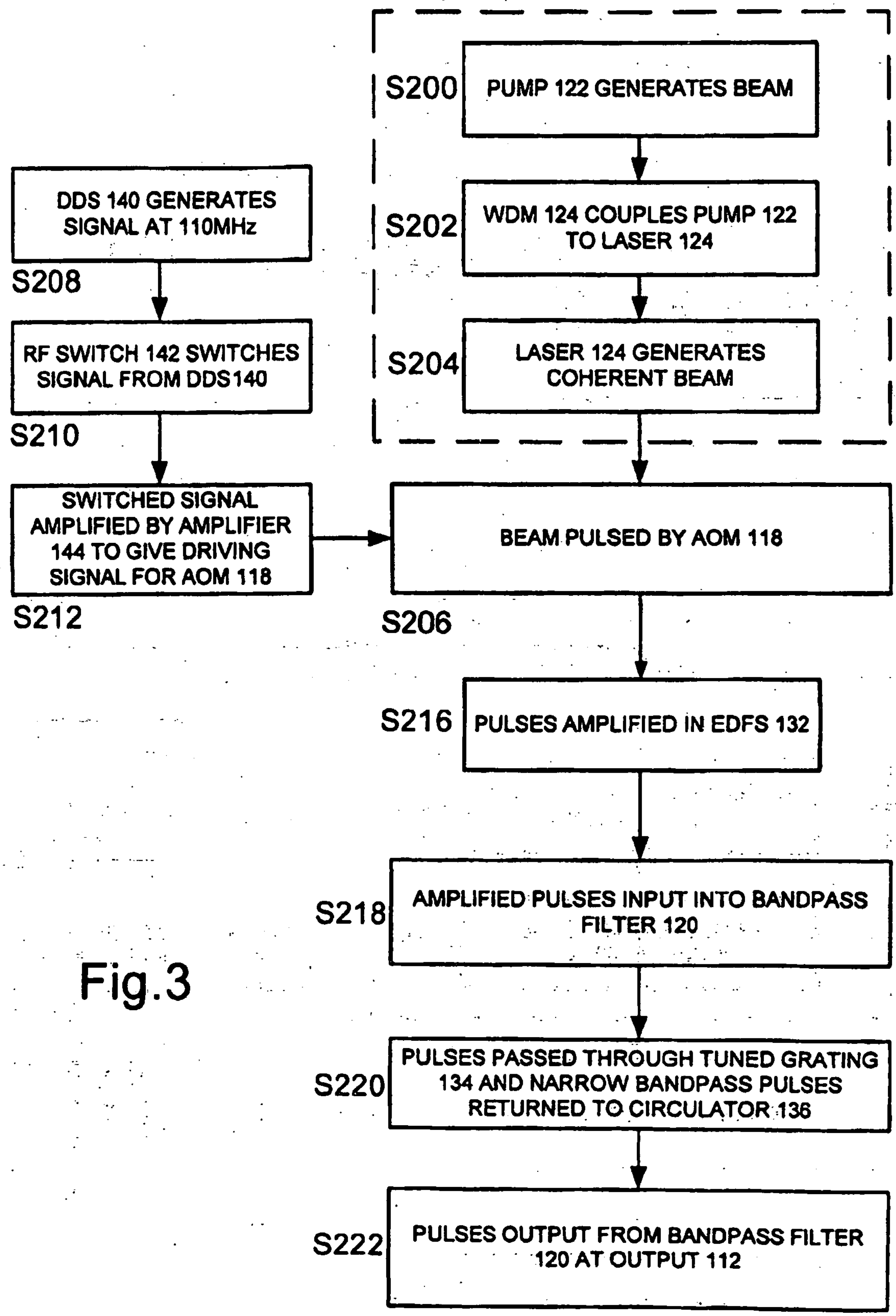
S200
PUMP 122 GENERATES BEAM
S202
WDM 124 COUPLES PUMP 122 TO LASER 124
S204
LASER 124 GENERATES COHERENT BEAM
DDS 140 GENERATES SIGNAL AT 110MHz
S208
RF SWITCH 142 SWITCHES SIGNAL FROM DDS140
S210
SWITCHED SIGNAL AMPLIFIED BY AMPLIFIER 144 TO GIVE DRIVING SIGNAL FOR AOM 118
S212
BEAM PULSED BY AOM 118
S206
S216
PULSES AMPLIFIED IN EDFS 132
S218
AMPLIFIED PULSES INPUT INTO BANDPASS FILTER 120
S220
PULSES PASSED THROUGH TUNED GRATING 134 AND NARROW BANDPASS PULSES RETURNED TO CIRCULATOR 136
S222
PULSES OUTPUT FROM BANDPASS FILTER 120 AT OUTPUT 112

Fig.3

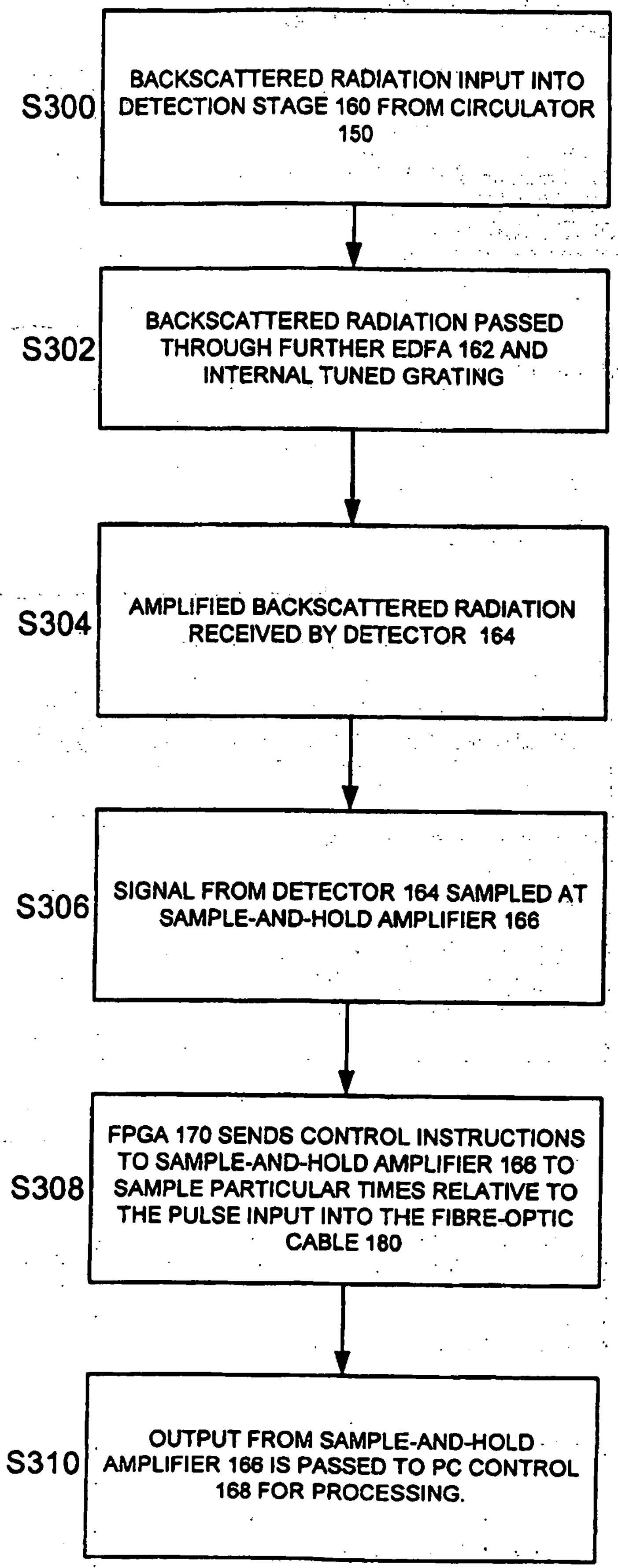
S300
BACKSCATTERED RADIATION INPUT INTO DETECTION STAGE 160 FROM CIRCULATOR 150
S302
BACKSCATTERED RADIATION PASSED THROUGH FURTHER EDFA 162 AND INTERNAL TUNED GRATING
S304
AMPLIFIED BACKSCATTERED RADIATION RECEIVED BY DETECTOR 164
S306
SIGNAL FROM DETECTOR 164 SAMPLED AT SAMPLE-AND-HOLD AMPLIFIER 166
S308
FPGA 170 SENDS CONTROL INSTRUCTIONS TO SAMPLE-AND-HOLD AMPLIFIER 166 TO SAMPLE PARTICULAR TIMES RELATIVE TO THE PULSE INPUT INTO THE FIBRE-OPTIC CABLE 180
S310
OUTPUT FROM SAMPLE-AND-HOLD AMPLIFIER 166 IS PASSED TO PC CONTROL 168 FOR PROCESSING.

Fig.4

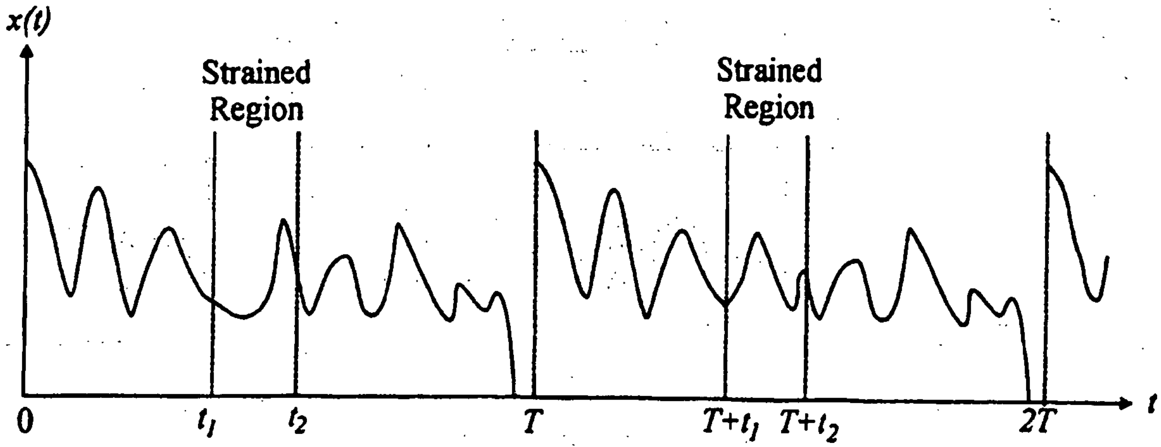

Fig.5a

Fig.5b

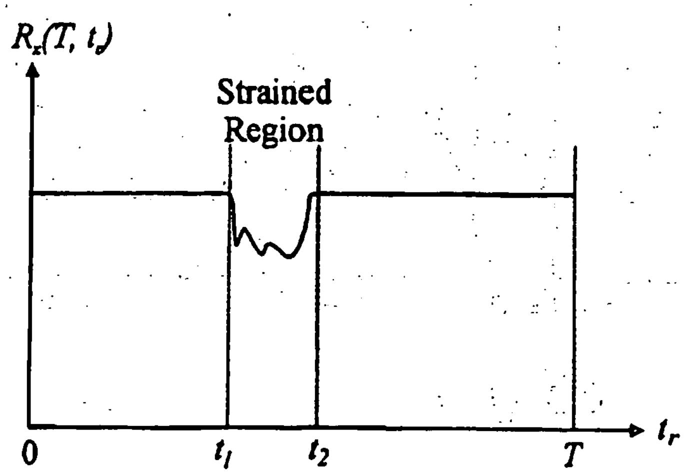

Fig. 6

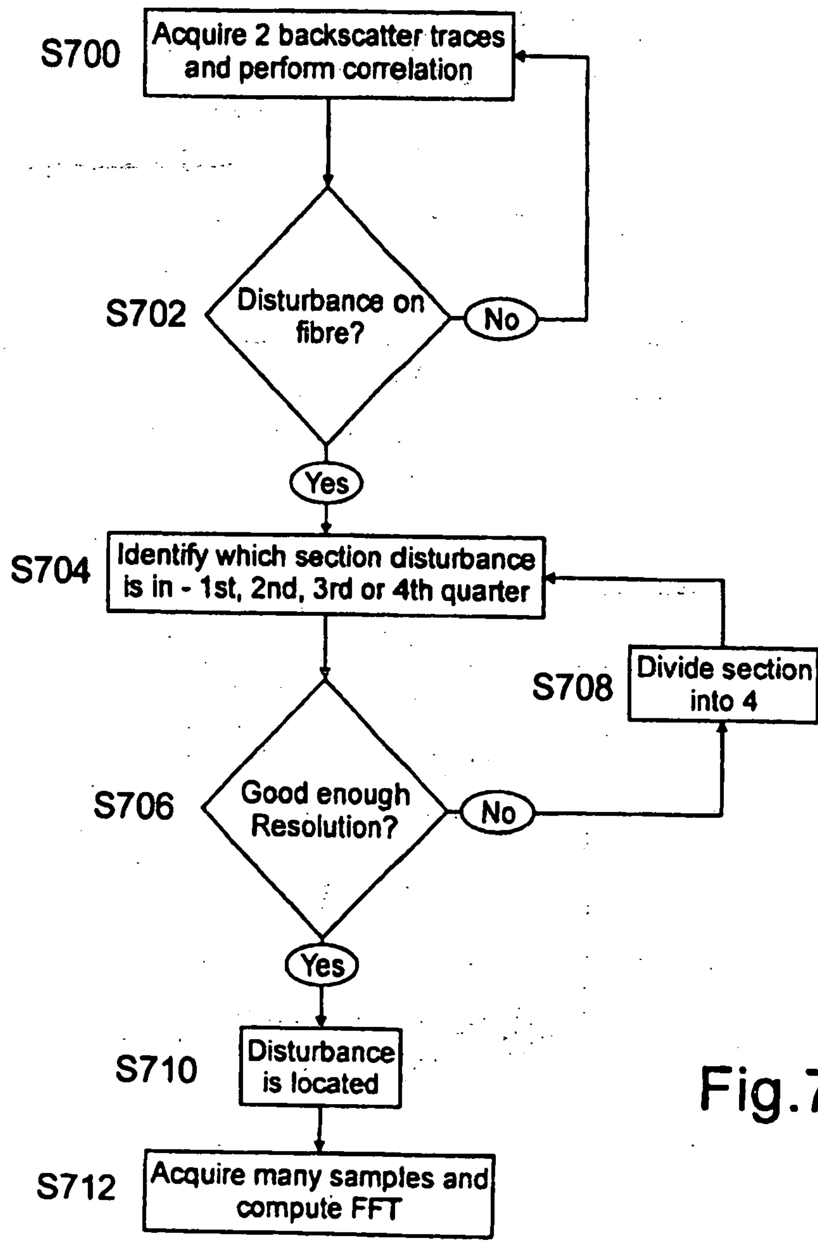
S700
Acquire 2 backscatter traces and perform correlation
S702
Disturbance on fibre?
No
Yes
S704
Identify which section disturbance is in - 1st, 2nd, 3rd or 4th quarter
S708
Divide section into 4
S706
Good enough Resolution?
No
Yes
S710
Disturbance is located
S712
Acquire many samples and compute FFT

Fig.7

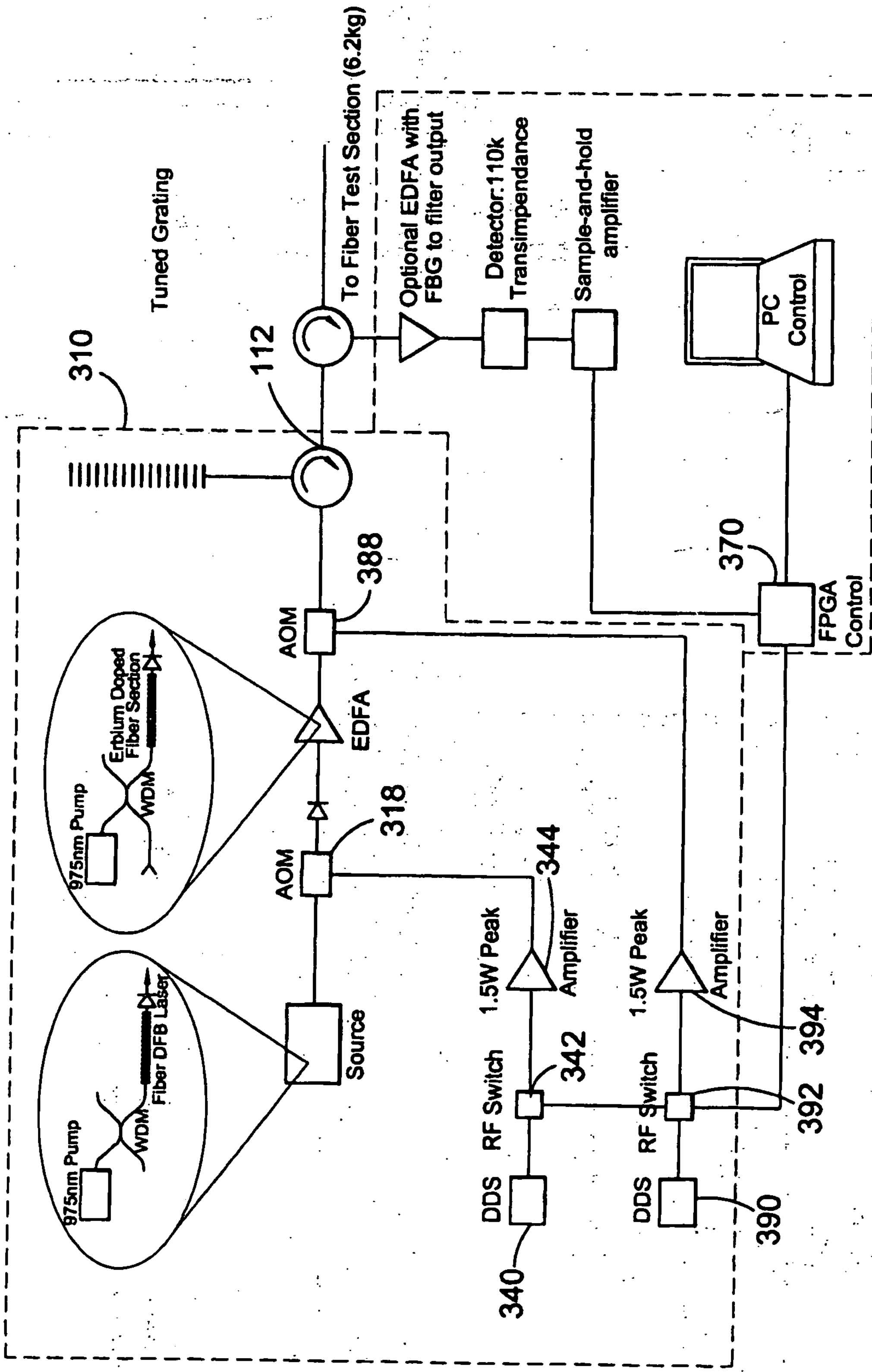
Tuned Grating
310
112
To Fiber Test Section (6.2kg)
Optional EDFA with FBG to filter output
Detector:110k Transimpendance
Sample-and-hold amplifier
PC Control
370
FPGA Control
388
AOM
EDFA
Erbium Doped Fiber Section
WDM
975nm Pump
318
AOM
344
1.5W Peak
Amplifier
Source
Fiber DFB Laser
WDM
975nm Pump
342
RF Switch
DDS
340
1.5W Peak
Amplifier
394
392
RF Switch
DDS
390

Fig. 8

Optic Communication or Transmission Media Sensing

Field Of The Invention

The present invention relates to remote detection of the location of a disturbance or change in physical configuration of an optic communication or transmission media such as a fibre-optic cable.

Background Of The Invention

Optical fibres contain microscopic inhomogeneities in the refractive index of the material. These inhomogeneities are typically less than an optical wavelength in size, and are fixed in the material of the fibre on manufacture. Inhomogeneities, with a very small refractive index difference such that the optical phase change is less than $\lambda/10$ compared with the average refractive index, give rise to similar backscattering.

These mechanisms set a theoretical minimum attenuation in fibre-optic cables due to statistical fluctuations of the refractive index.

It can be shown that, where a pulse of Gaussian beam profile with a temporal width τ is launched down the fibre, the total backscattered power P_s at time t is given by:

$$P_s = \frac{1}{2}\alpha_s v_g \tau P_0 e^{-\alpha v_g t} S \qquad [1]$$

where α_s is the attenuation constant representing loss due to Rayleigh scattering, v_g is the group velocity of light in the core, P_0 is the power launched at the sending end of the fibre, α is the overall attenuation constant (for modern fibres $\alpha \approx \alpha_s$) and S is the fraction of the scattered light which is recaptured by the fibre in the reverse direction.

For a step-index signal-mode fibre it can be shown that:

$$0.21\frac{n_1^2 - n_2^2}{n_1^2} \leq S \leq 0.24\frac{n_1^2 - n_2^2}{n_1^2} \qquad [2]$$

wherein n_1 and n_2 are the core and cladding refractive indices respectively. For a typical telecommunications fibre n_1=1.46 and n_2=1.44. Taking these values and assuming a mid-point coefficient of $\frac{0.21+0.24}{2}$ gives $S\approx0.0063$.

The above analysis assumes an incoherent source is used to generate the pulse. However, this is not necessarily the case; some types of source have coherence lengths of several kilometres. Coherent illumination causes a change in the properties of the Rayleigh backscatter. The illumination can be said to be coherent when the coherence length is longer than the pulse length. Because each scattering point is excited from a coherent source, the scattered light interferes, constructively or destructively, resulting in localised maxima and minima in the backscatter trace: this phenomenon is referred to as coherence noise or "fading" noise. As the characteristics of the backscatter trace are determined by the relative phase relations of a large number of backscattered waves from fixed locations, the short-term signal is stable unless the phase relations are changed. It is therefore not possible to remove fading noise simply by averaging over a large number of pulses, but some parameter which changes the phase relation between scattering sites must be varied over the averaging, most commonly the wavelength of the incident light.

By launching a pulse of light down the fibre and using time-of-flight analysis, the spatial location of optical features can be found. This technique is known as Optical Time Domain Reflectometry.

Conventional Optical Time-Domain Reflectometry (OTDR), makes use of pulses of incoherent radiation successively input into a fibre-optic cable. The backscatter of the

pulses, caused by the inhomogeneities in the cable, is detected and the amplitude of the backscattered radiation is averaged over many pulses to obtain an attenuation profile for the cable.

However, conventional OTDR is strain sensitive only where the strain impairs the guiding properties of the fibre. Also, very many pulses must be used in order to obtain a sufficient signal to noise ratio, and so the technique is unsuitable for audio frequency measurements.

It is an object of the invention to provide an improved system for remote detection of the presence and/or location of a disturbance i.e. a change in physical configuration of optic communication or transmission media such as a fibre-optic cable.

Summary Of The Invention

The present invention provides a method and apparatus for sensing disturbances in an optic communication or transmission media such as a fibre optic cable. Such a fibre can be used in a variety of technical fields, for example, the communication industry in order to prevent damage by excavation, or sensing technologies e.g. stretch sensors. Pulses of coherent light are input to the media. Radiation from the pulses is backscattered by inhomogeneities in the media and the backscattered radiation from the pulses is detected and compared or correlated for different pulses.

The invention provides an apparatus and method which in one embodiment can detect small strains in a fibre-optic cable. In an embodiment of the invention, this is done by sending a pulse of radiation along the fibre-optic cable, and detecting the backscattered signal from the input pulses as a function of time, rather than averaging the backscattered amplitude over many pulses. Therefore, varying strains on the fibre, which displace a number of the scattering inhomogeneities in the fibre and thus cause local variations in the backscatter trace, can be detected as an intensity modulated signal directly related to the strain at that location.

The pulse can also be compared with a reference of backscattered radiation from the cable, or a derived version of the reference, in order to indicate a disturbance by any differences between the reference and the backscatter from the pulse.

In an embodiment of the invention, a plurality of pulses can be input into a fibre-optic cable, and comparison and/or correlation analysis can be carried out on these pulses to determine the location of a change in the physical configuration of the fibre-optic cable. Correlation of backscatter from multiple pulses gives an accurate result on the location and/or existence of a strain because random features of single backscatter profiles for each pulse can be ignored and strains detected over more than one pulse can be emphasised without averaging over many pulses, which would destroy the location information held in the delay between input of the pulse and detection of the backscattered radiation.

If identical pulses are sent down the fibre-optic cable, then the backscattered radiation caused by each pulse received by the detector, as a function of time, should also be identical, as the inhomogeneities are fixed in the fibres on manufacture.

However, if there is a disturbance to the fibres, such as a strain or bend in the cable, there will be a change in the configuration of the inhomogeneities within the fibres, causing an alteration in intensity of the backscattered radiation as a function of time. This will cause a reduction in the correlation of backscattered pulses as the configuration of the cable changes.

Such a reduction of correlation can indicate not only that a disturbance is occurring, but also the location of the disturbance, due to the fact that the backscattered radiation is detected as a function of time, and the time taken for the backscattered radiation to return to the input end of the cable is indicative of the distance along the cable from the input end that the disturbance occurs.

The pulses can be input to the cable at acoustic frequencies to identify acute disturbances to a cable, for example excavation of the ground surrounding or close to the cable.

The pulses can be input to provide continuous monitoring of a cable, so that any disturbance can be detected as soon as it occurs. With such monitoring, as well as acute disturbances, long term changes in the configuration of the cable, caused by slowly altering physical effects such as subsistence and shifting of the ground in which the cable is buried, can be monitored. Such monitoring could be carried out by correlating between pulses over longer time periods, for example days, weeks or months.

An embodiment of the invention has a source of pulses of coherent radiation. The pulses may be of a duration in the range of 50ns to 50μs. The range of duration may also be between 100ns and 1μs, or between 150ns and 500ns. The range of durations may be any non-zero time up to the pulse repetition rate. The spatial resolution is proportional to the pulse duration.

In an embodiment of the invention, the source comprises a laser generator, an amplifier and a high speed switch to pulse the laser generated beam. A pulsed beam generator may alternatively be used, or the pulses may be generated remote to the apparatus of the invention. All that is needed is a source of pulses of coherent radiation.

An embodiment of the invention also has an input and receiving stage, which may be comprised in a single unit. This unit may be a circulator. Alternatively, the input and receiving stage may be separate input and receiving units. This stage may also comprise an output unit.

An embodiment of the invention comprises a detection stage to detect the backscattered radiation from the pulses. The detection stage may include only a detector to detect the backscattered radiation from each pulse. The detector detects the intensity of the backscattered radiation. The detection stage may also comprise a processor to process the detected backscatter from the pulse as a function of time and may also correlate the backscatter with previous pulses and may give a signal indicative of the presence of a disturbance and/or its location.

The invention, in particular the detection stage, may also have one or more sample-and-hold amplifiers, which provide samples of the backscattered radiation from the pulses at predetermined times.

Alternatively, the processing of the detected backscatter may be processed externally to the invention, with only raw data being output from the apparatus of the invention.

Alternatively, digital signals may be processed, rather than analogue signals.

One or more computers or dedicated processors can be used to control some or all aspects of the invention.

One or more processors may also be used to calculate the comparison or correlation between backscatter caused by the pulses and to give an indication of the existence and/or location of a disturbance.

The invention also consists in other combinations of individual features not explicitly described herein.

For the avoidance of doubt, the fibre-optic cable itself does not form part of embodiments of the invention, but is used with the invention, and disturbances on the cable detected and/or located by the invention. Additionally, although a fibre-optic cable has been referenced to be used with the invention, other types of optical communication or transmission media may be used, if the features of the media are static or predictable.

Brief Description Of The Drawings

Embodiments of the invention will now be described, purely by way of example, with reference to the accompanying drawings, in which:

Figure 1 shows a diagram of an apparatus according to a first embodiment of the invention;

Figure 2 shows a flow diagram showing a method of operation of the first embodiment of the invention;

Figure 3 shows a flow diagram showing the operation of a source of the first embodiment of the present invention;

Figure 4 shows a flow diagram showing the operation of a detection stage of the first embodiment of the present invention;

Figure 5a shows a schematic graph representative of the backscattered radiation obtained from a cable and detected by the first embodiment of the invention as a function of time;

Figure 5b shows a further schematic graph representative of the backscatter from pulses input into a cable and detected by the first embodiment of the invention as a function of time at a different time from the same cable;

Figure 6 shows a schematic graph of correlation of the graphs of figures 5a and 5b;

Figure 7 shows a flow diagram according to a second embodiment of the invention; and

Figure 8 shows an apparatus according to a third embodiment of the invention.

Detailed Description of Embodiments Of The Invention

Figure 1 shows an apparatus according to a first embodiment of the invention. The apparatus comprises a source 110, a circulator 150 and a detection stage 160.

The source 110 has an output 112, which provides pulses of coherent radiation, and the source output 112 is optically coupled to the circulator 150. The circulator 150 is also optically coupled to the detection stage 160, and to a fibre optic cable 180. The circulator 150 directs radiation from the source 110 into the fibre-optic cable 180 and

receives radiation returned from the fibre-optic cable 180 and directs the received radiation into the detection stage 160.

The circulator 150 has an input stage and a receiving stage, which input the pulses into the fibre-optic cable 180 and receives the backscattered radiation caused by the pulses from the cable 180 respectively. In the first embodiment, the input stage and receiving stage is the same unit. However, alternatively, separate units could be provided to perform the same function.

The detection stage 160 detects the intensity of the backscattered radiation input from the circulator 150 as a function of time.

In addition to the output 112, the source 110 comprises a light generator 114 supplying an erbium doped fibre amplifier (EDFA) 116 via an accousto-optic modulator (AOM) 118. The EDFA 116 is connected to a bandpass filter 120 which comprises output 112.

The light generator 114 comprises a pump 122 supplying a fibre distributed feedback laser 124 via a Wavelength Division Multiplexer (WDM) 126 coupled between the two and an isolator 128. The pump 122 generates radiation at a wavelength of 975nm. Other frequencies of radiation could also be generated by using a different pump and WDM and laser. The radiation generated by the pump 122 is fed into the WDM 126 and from there into the laser 124. The laser 124 then outputs a beam of radiation at a wavelength of 1550.116nm. The isolator 128 prevents radiation returning into the laser 124. Wavelengths other than this could also be used in the invention.

The radiation output from the generator 114 is controlled by AOM 118 which pulses the beam from the generator 114. The AOM 118 is controlled by a Radio Frequency (RF) switch 142, which modulates a signal generated by a DDS (direct digital synthesiser) 140, and the modulated signal produced by the RF switch 142 acting on the generated signal is amplified by an amplifier 144 to a power of 1.5W peak before being input into the AOM 118. AOM 118 is driven at 110MHz with the RF switch turning the 110MHz signal on and off, but other frequencies could alternatively be used, as appropriate. Other sources producing pulsed laser radiation could also be used in the invention.

The RF switch 142 is controlled by a control stage 170. The control stage 170 controls the opening ratio and timing of the AOM 118 via the RF switch 142. The control stage 170 is also connected to the detection stage 160 so as to synchronise the source 110 and detection stage 160.

The EDFA 116 comprises a second pump 128 at the same wavelength as the first pump 122. Other wavelengths could also be used. An erbium doped fibre section 132 is connected to the second pump 128, via a second WDM 130, and amplifies the pulses from the AOM 118. In the present embodiment, output from the EDFA 116 is then passed through the narrow bandpass filter 120. The bandwidth of the filter 120 is, in the present embodiment, 0.3nm. The filter 120 comprises a fibre Bragg grating (FBG) 134, and a circulator 136. The FBG 134 removes amplified spontaneous emission (ASE) from the EDFA 116 and only allows light within the bandwidth to re-enter the circulator 136 and be output from the output 112 of the source 110.

The EDFA 116 gives a gain of 30 dB with pulses 200ns in duration. An AOM 118 with a 90% transition time of ~25ns and a separation between pulses of at least 50μs is provided.

The pulses produced by the source 110 are at a power such that non-linear effects are small. The source produces pulses of ~1W for ~200ns, which gives an average energy of the pulses of 0.2μJ, keeping non-linear effects low and within tolerances.

The pulses output from the source 110 at output 112 are input into an input and receiving stage, which in this embodiment is the circulator 150. The circulator 150 inputs pulses received from the source 110 into the fibre optic cable 180, to which the circulator 150 is coupled.

A proportion of the radiation backscattered within the fibre-optic cable 180 is received back at the circulator 150. This backscattered radiation is output from the circulator 150 to the detection stage 160.

The detection stage 160 comprises a further EDFA 162 to amplify the signal from the circulator 150. The further EDFA 162 is the same as EDFA 116 in the source 110, except that a fibre Bragg grating (not shown), which is the same as grating 120, is included within the further EDFA 162.

Alternatively, the further EFDA 162 may be omitted, if the intensity of the backscattered radiation from the fibre-optic cable 180 is sufficient for detection to be achieved without the further EDFA, at a suitable signal to noise ratio.

A detector 164 is connected to the output of the further EDFA 162 and the signal output from the detector 164 is output to a sample-and-hold amplifier 166, which is controlled by the control stage 170, which in this embodiment comprises a FPGA controller, to sample the signal from the detector 164 at a particular time.

The sample-and-hold amplifier 166 is thus synchronised with the AOM 118 of the source 110, so that the time after the pulse enters the fibre-optic cable 180 is known, and the time delay from entry into the fibre-optic cable 180 to backscatter to the detection stage 160 is also known. The distance along the fibre 180 that the pulse has travelled before being backscattered can be determined from the time delay. The sample-and-hold amplifier is timed to capture the signal from a specific region of the fibre. More than one sample-and-hold amplifier may be used, and these may be used to capture signals from more than one region of the fibre.

The signal sampled by the sample-and-hold amplifier 166 is input into the control stage of the FPGA controller 170, which is, in turn, controlled by a PC control 168. The sampled signal is received by the PC control 168 and processed as will be described below.

A method of operation of the first embodiment of the invention will now be described with reference to Figures 2 to 4 of the drawings.

Figure 2 shows a flow diagram of an overall operation of the first embodiment.

The source 110 generates pulses at S100. Each pulse enters the circulator 150 at S102 and is output into the fibre-optic cable 180 at S104.

Each pulse travels along the fibre-optic cable 180, with some backscattering along its length. The backscattered radiation travels back along the fibre-optic cable 180, and re-enters the circulator 150 at S106. The circulator 150 outputs the backscattered radiation received to the detection stage 160, and the detection stage 160 detects the backscattered radiation, at S108.

Figure 3 shows a flow diagram showing a method of operation of the source 110 of the first embodiment.

Within the generator 114, the pump 122 creates light with a wavelength of approximately 975nm at S200. The WDM 126 creates an output for pumping the DFB laser 124 at S202, and the fibre DFB laser 124 creates a coherent beam of radiation with a line width of approximately 30kHz, giving a coherence length of over 6km in fibre, which is output from the generator 114 at S204.

The beam from the generator 114 is then pulsed by AOM 118 at S206. AOM 118 is controlled by the control stage 170. The DDS 140 produces a RF signal at 110MHz at S208. The RF switch 142, controlled by the control stage 170, switches the RF signal of the generated signal at S210. This signal is amplified by the 1.5W peak amplifier 144 at S212.

The beam is therefore pulsed by the AOM 118 according to the RF switch 142 signal, which is controlled by the control stage 170. The AOM 118 provides pulses of a length of approximately 200ns, with a separation between pulses of more than 50μs.

The further EDFA 130 then amplifies the signal at S216. The amplified pulse, with a power of approximately 1W, is then passed through the circulator 136 of the bandwidth filter 120 at S218. The pulse is filtered by the fibre Bragg grating 134 at S220, in order to remove amplified spontaneous emission noise from the EDFA 116.

The bandwidth of the filter is 0.3nm and each pulse output from the source 110 has a duration of approximately 200ns, which corresponds to a spatial extent of the pulse of 40m within the fibre-optic cable 180. The power of the amplified source 110 is approximately 1W, giving an energy of each pulse of 0.2μJ. The wavelength of the input pulse is 1550.116nm with a line width of 30kHz.

Figure 4 shows a method of operation of the detection stage according to the first embodiment of the invention.

The backscattered radiation from the circulator 150 is input into the detection stage at S300. The radiation is passed through the further EDFA 162 at S302 to amplify the signal and filtered to remove any radiation at a wavelength of other than 1550.116nm.

The amplified radiation is then input into the detector 164 at S304. In the present invention, the detector 164 is a fibre-coupled photodiode detector with a transimpedance of 110kΩ. However, other detectors may also be used.

The detected signal is output from the detector 164 to the sample-and-hold amplifier 166 at S306. The sample-and-hold amplifier, comprises a sample-and-hold device, giving a small-signal bandwidth of 15 MHz. An 8^{th} order, progressive-elliptic, low-pass filter (Linear Technologies LTC1069-1) then removes signal components above 3 kHz, effectively smoothing the transitions between samples. The output is buffered by an op-amp stage giving 20 dB gain over 3 kHz bandwidth. The sample-and-hold device generates 150 μV RMS noise, the low-pass filter 110μV RMS, and the operational amplifier 15 nV/$\sqrt{\mathrm{Hz}}$ at the input. Alternatively, a linear filter can be used.

The total RMS noise of the sample-and-hold amplifier is therefore:

$$10 \times \left[150^2 + 110^2 + \left(0.015 \times \sqrt{3000}\right)^2\right]^{1/2} = 1900\mu\mathrm{V} \qquad [3]$$

This is equivalent to an optical input of approximately 2 nW. This is two orders of magnitude smaller than the optical power required to give shot-noise limited detection (0.53 μW) so no significant noise is added by the sample-and-hold amplifier. The total noise is reduced because the detector noise above 3 kHz will be suppressed by the filter elements.

In order to satisfy the Nyquist criteria at the maximum signal frequency, the output must be sampled at a minimum of 6 kHz, setting the maximum sensor length to (Group velocity)x(Round trip duration) = $\dfrac{2 \times 10^8}{2 \times 6000} = 17$ km. For example, with a 6.2 km fibre-optic cable 180, the repetition rate is 14 kHz. Longer sensors are possible by accepting a reduction in the sensor bandwidth.

The sample-and-hold amplifier 166 receives control instructions from the FPGA 170 at S308 to sample particular times relative to the pulse input into the fibre-optic cable 180.

The output from the sample-and-hold amplifier is then passed to the PC (control) 168 at S310 for processing.

Figures 5a and 5b show schematic results representative of the first embodiment described above. These figures show that the graph of the intensity of the detected backscattered radiation against time differs between figure 5a and figure 5b.

Assuming that the pulse enters the fibre-optic cable at *0* in Figure 5a and at *T* in figure 5b, in the region between t_1 and t_2 and $T+t_1$ and $T+t_2$, the signal is different, indicating that the physical configuration of the fibre-optic cable 180 has changed between *0* and *T* at a distance corresponding to the time t_1 taken for the pulse to travel along the fibre-optic cable 180 and back to the detector.

The two pulses can then be compared, and any detected differences used to indicate a disturbance of the fibre, and the region or location of the fibre at which the disturbance has occurred. In order to simply detect the existence of a change in the physical configuration of the fibre optic cable, the whole of the sum of backscattered radiation

from each pulse may be compared. A change in this sum between pulses can indicate a change in the physical configuration of the fibre. It is possible to sum the differences in the intensity of radiation backscattered by different pulses to obtain an indication of the strain in the fibre.

Further, in the above embodiment, an auto-correlation can be found between pulses. Such correlation is not essential to the invention.

The auto-correlation function can be defined as

$$R_x(\tau) = < x(t)x(t+\tau) > . \quad [4]$$

The triangular brackets denote ensemble averaging, which may be approximated by a time average. In order to identify changes in the backscatter trace it is clearly only of interest to consider the case when $\tau = T$. Disturbance location may be achieved by taking the average over a fraction of the total backscatter trace. The duration of the averaging period will limit the spatial resolution (assuming it is longer than the pulse duration). In order to maintain spatial resolution of the simple system the averaging should take place over the pulse duration, t_p. Re-writing the average in terms of an integral, we therefore obtain that

$$R_x(\tau = T, t_r) = \frac{1}{t_p} \int_{t_r}^{t_r+t_p} x(t)x(t+T)dt \quad [5]$$

where the time t_r gives the range. The signal is not continuous, but a digitally sampled signal and so the integral is replaced by summation over the requisite number of samples. The idealised result for the case of Figures 5a and 5b is shown in Figure 6. The correlation is constant in the un-strained regions and reduces where the waveforms differ in the strained region.

Implementing the above technique in real time requires high data processing rates. Therefore, a less computationally intensive algorithm for disturbance location may be

used. A second embodiment of the present invention uses the first embodiment method and apparatus, but additionally divides the sensing fibre into a number of relatively large sections. The principle of this second embodiment is shown in a flow diagram in Figure 7.

At S700 the PC control 168 chooses two different backscatter traces obtained from the detection stage 160. A correlation, as described above, or another correlation method, is carried out on the two traces.

The correlation result is analysed for any reduction in correlation, which would indicate a disturbance on the fibre-optic cable 180 at S702. If no reduction in the correlation is detected for the trace as a whole, the system returns to S700 and repeats.

If a reduction in correlation is detected, a disturbance is identified and the system detects which section the disturbance is in by breaking the backscattered trace into, for example, four regions separated by time, and analysing the correlation in each region until the region in which the fall in correlation occurred has been identified at S706.

The region identified as having the fall in correlation is then divided into four at S708, and S704 and S706 are then repeated.

The S706-S708 loop is repeated until the resolution of the disturbance is sufficient, at which point the disturbance is located at S710.

Finally, at S712 the whole sequence is repeated to give many samples, which are then fast fourier transformed to obtain a frequency spectrum of the signal.

Each of these can then be interrogated using the above correlation technique but with the averaging occurring over the whole section. When a disturbance is found in one of the sections the system then concentrates on this section, successively dividing it into smaller and smaller sections until the disturbance is located to sufficient spatial resolution. This process may be accomplished by either reprocessing the original data or using newly acquired data. Once the disturbance is located, a number of

measurements can be made at that location to determine the frequency spectrum of the disturbance. Depending on the time taken to carry out these operations it may be desirable to periodically re-scan the entire fibre to detect any additional disturbances that could then be located in parallel, using a number of sample and hold amplifiers.

Figure 8 shows a third embodiment of the invention. The third embodiment is similar to the first embodiment and the additions of the second embodiment may also be used with this third embodiment.

Elements of the third invention corresponding to those of the first embodiment will retain the first embodiment numbering. The third embodiment differs from the first embodiment in that a second AOM 388 is included in the source 110 between the EDFA 116 and the bandwidth filter 120.

The third embodiment comprises drive signal generation elements for the second AOM 388. Additionally, the first AOM 318, DDS 340, RF switch 342 and amplifier 344 are also modified from that described in the first embodiment.

The drive signal generation elements for the second AOM 388 are the same as those for the first AOM 118 of the first embodiment. A DDS 390 generates a signal at 80MHz, an RF Switch 392, which is controlled by control stage 370, switches the signal from the DDS 390. The resulting signal is amplified by an amplifier 394 before being input into the second AOM 388.

As stated above, the first AOM 318, DDS 340, RF switch 342 and amplifier 344 are modified from that described in the first embodiment. DDS 340 generates a signal at 80MHz, rather than 110MHz. RF switch 342 receives control signals from control stage 370, and switches the generated signals from the DDS 340, which are then amplified using amplifier 344 with a power of 2W peak.

The effect of the addition of the second AOM 388 is to block amplified spontaneous emission from the first EDFA 116 between pulses, so reducing ASE in the fibre-optic

cable with the backscattered radiation caused by the pulses generating noise in the detection stage.

Other than the above, the third embodiment may operate in generally the same way as described in relation to the first embodiment.

Instead of AOMs, other types of optical switches can alternatively be used in the invention.

Any discussion of prior art throughout the specification is not an admission that such prior art is widely known or forms part of the common general knowledge in the field.

The present invention has been described above purely by way of example, and modifications can be made within the spirit of the invention. The invention also consists in any individual features described or implicit herein or shown or implicit in the drawings or any combination of any such features or any generalisation of any such features or combination, which extends to equivalents thereof.

Unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise", "comprising", and the like, are to be construed in an inclusive as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to".

CLAIMS:

1. A sensing apparatus for sensing disturbances in an optic communication or transmission media, the apparatus comprising:

a source of pulses of coherent radiation;

an input and receiving stage connected to the source to input pulses of radiation into the optic communication or transmission media at a first end and to receive radiation backscattered by the optic communication or transmission media caused by the pulses input into the optic communication or transmission media;

a detecting stage connected to the input and receiving stage to detect a property of the backscattered radiation caused by the pulses as a function of the time elapsed after a predetermined time; and

a comparison stage to compare the detected backscattered radiation caused by different pulses input into the optic communication or transmission media.

2. A sensing apparatus according to claim 1, further comprising an indicating stage connected to the detecting stage to indicate the distance along the optic communication or transmission media at which a disturbance has occurred using the time elapsed between each pulse entering the optic communication or transmission media and detecting the backscattered radiation caused by the pulse and indicative of a disturbance to the optic communication or transmission media.

3. A sensing apparatus according to claim 1 or claim 2, further comprising an indication generator to output a signal indicative of the presence of a disturbance to the optic communication or transmission media based on the result of the comparison.

4. A sensing apparatus according to claim 3, wherein the indication generator is arranged to indicate the distance of the disturbance along the optic communication or transmission media from the first end, based on the result of the comparison.

5. A sensing apparatus according to any preceding claim, further comprising at least one sample and hold amplifier, to repeatedly sample a value of the output of the detection stage to hold the value for output until a new sample is taken.

6. A sensing apparatus according to any preceding claim, wherein the detecting stage is adapted to detect the intensity of the backscattered radiation caused by the pulses as a function of time.

7. A sensing apparatus according to any preceding claim, further comprising a processor to control one or more of the source, input and receiving stage, detecting stage and comparison stage.

8. A sensing apparatus according to any preceding claim, wherein the input and receiving stage comprises a circulator.

9. A sensing apparatus according to any preceding claim, wherein the source comprises a laser, an amplifier and a high speed switch.

10. A sensing apparatus according to any preceding claim, wherein the comparison stage is adapted to correlate the detected backscattered radiation, as a function of time, caused by different pulses input to the communication or transmission media.

11. A method of sensing disturbances in an optic communication or transmission media, comprising;

inputting pulses of coherent radiation into the optic communication media;

receiving backscattered radiation from the optic communication or transmission media caused by the pulses input into the optic communication or transmission media;

detecting a property of the backscattered radiation as a function of the time elapsed after a predetermined time; and

comparing the intensity of detected backscattered radiation of different pulses input into the optic communication or transmission media.

12. A method according to claim 11, further comprising determining the distance along the optic communication or transmission media at which the disturbance has occurred by using the time elapsed after said predetermined time.

13. A method according to one of claim 11 or claim 12, wherein successive pulses are correlated.

14. A method according to any one of claims 11 to 13, wherein said predetermined time is the time after entry of the pulse into the optic communication or transmission media.

15. A method according to any one of claims 11 to 14, further comprising sampling the detected signals at discrete intervals and processing the sampled signals.

16. A method according to any one of claims 11 to 15, wherein the comparison is a correlation of detected backscattered radiation, as a function of time, caused by different pulses input into the optic communication or transmission media.

17. A sensing apparatus for sensing disturbances in an optic communication media, the apparatus comprising:

generation means for generating pulses of coherent radiation;

input and receiving means for inputting the pulses of radiation into the optic communication or transmission media and for receiving radiation backscattered by the optic communication or transmission media caused by the pulses into the optic communication or transmission media;

detection means for detecting the intensity of the backscattered radiation caused by the pulses as a function of the time elapsed after a predetermined time; and

comparing means for comparing the backscattered radiation caused by different pulses input into the optic communication or transmission media.

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Application No: GB 0311333.9
Claims searched: all

Examiner: Dr E.P. Plummer
Date of search: 17 November 2003

Patents Act 1977 : Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance	
X	1-4,6,7, 10-17	EP 0887624 A3	ANDO ELECTRIC whole document
X	1,11,17 at least	NL 8401361	NEDERLANDSE CENTRALE ORGANISATIE VOOR TOEGEPAST-NATUURWETENSCHAPPELIJK ONDERZOEK TE 'S-GRAVENHAGE whole document
X	1,11,17 at least	US 6310702	MINAMI et al whole document
X	1,11,17 at least	WO 91/02959 A1	BRITISH TELECOMMUNICATIONS whole document
X	1,11,17 at least	US 6385561 B1	SORAGHAN et al whole document
X	1,11,17 at least	US2002/0063866 A1	KERSEY et al whole document
X	1,11,17 at least	EP 0806642 A1	DAIMLER BENZ AEROSPACE whole document

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X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{V}:

G1A, H4D, H4B

Worldwide search of patent documents classified in the following areas of the IPC^{7}:

G01K, G01M, G01D, G01N, G01D, G01H, G01L, H04B

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Application No:	GB 0311333.9	**Examiner:**	Dr E.P. Plummer
Claims searched:	all	**Date of search:**	17 November 2003

The following online and other databases have been used in the preparation of this search report:

Online: WPI, EPODOC, PAJ